Regional Synthesis of the Sedimentary Thermal History and Hydrocarbon Maturation in the Deepwater Gulf of Mexico

Final Report

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Introduction

The goal of this project was to construct regional models for the sedimentary thermal history and hydrocarbon maturation in the Deepwater Gulf of Mexico. In order to achieve the goal, our strategy was first to constrain the geothermal heat flow at as many locations as possible in the deepwater Gulf. The heat flow can be determined as the product of two sets of quantities that can be measured separately below the seafloor: the geothermal gradient and the thermal conductivity variation with depth. We attempted to constrain the two at each location of the deepwater wells of which the data have been released to the public. Michael Jones, graduate student at Texas Tech University, took a leading role in execution of this project. His master's thesis attached to this report describes the outcome of this research and explains the methodologies taken in detail.

We compiled data on present-day temperature distribution, thermal properties, and accumulation history (stratigraphy) of the sediments. A large portion of such data were obtained either directly or indirectly from the well logs archived at the MMS New Orleans office. Especially the bottom-hole temperature (BHT) data were important, because they provided constraints to the temperature distribution within deep sediments (i.e., the geothermal gradient). We also had access to over 200 geothermal heat flow data from the deepwater Gulf, which were made available by TDI-Brooks International, Inc. in College Station, Texas. These data were obtained by probe measurements farther offshore from the areas that been drilled.

Analyses of Bottom-hole Temperature Data

During the initial phase of the project, we focused on analyzing the BHT data. A BHT is not the same as the virgin rock temperature (VRT) of the sediment at the depth where the measurement is taken. BHT tends to be significantly lower, because, during the drilling operation, the sediment is cooled by circulation of drilling fluid. If multiple BHT measurements were taken at different times at the same depth, it is relatively easy to make the correction by mathematically extrapolating the trend of the temperature recovery since the shut in (the so-called Honor plot method, (Jaeger, 1961). But, the vast majority of our BHT data gave only one measurement at a depth. In the past, only (Deming and Chapman, 1988) attempted to correct such single-measurement BHTs by making certain assumptions about the way drilling activity influences the borehole temperature. Their correction yielded reasonable results for the data set they obtained in Utah and Wyoming.

We were not certain if the methodology of Deming and Chapman (1988), which was tested only with a small number of data, is directly applicable to the BHT data from the deepwater Gulf. We conducted a more thorough test of their methodology, using a larger volume of data sets that were previously published. These data sets yielded multiple BHT measurements per depth, which allowed us to compare the correction using the Honor plot method with Deming and Chapman's method. Our result showed that the two types of corrections were in general agreement (within 5-10%).

By adopting the methodology of Deming and Chapman (1988), we were able to estimate VRTs for 88 wells located in the deepwater Gulf of Mexico. However, roughly a half of these wells yielded only one VRT estimate for each. In order to determine the geothermal gradient, we needed temperature to be measured/estimated at two or more different depths. If there is only one sub-bottom temperature data available, one could use temperature data measured at the seafloor in estimating the thermal gradient. Thus, we compiled such hydrographic data previously made available in the Gulf of Mexico. We used two data sets. The first was the bottom-water temperature data obtained during the heat flow probe cruises by TDI-Brooks International. The second was the expendable bathy-thermograph data archived in the World Ocean Database 2001 of the National Oceanographic and Atmospheric Administration. Using these two data sets, we produced a map of bottom-water temperature for seafloor deeper than 1000 m in the northern Gulf of Mexico. Data from shallower depths were not included in the analysis, because based on my previous experience (Nagihara et al., 1992), we knew that there is about 0.3° C of seasonal fluctuation in the water temperature at 1000 m depth on the Texas-Louisiana continental slope. But for the water depth greater than 1500 m, we believe that the compiled map allows us to constrain the seafloor temperature within 0.2° to 0.3° C. For the wells where only one VRT estimate is the available, we used the bottom-water temperature as the second constraint necessary for the geothermal gradient determination.

There were several wells that did not show a linear temperature vs. depth profile. We believe that there are two possible explanations. The first is the human errors made in recording the data and other well header information. The second is presence of salt structures. Salt has a thermal conductivity three to four times greater than other sedimentary rock. Thus, the thermal gradient within a layer of salt is very different from that above and below.

Estimating Sedimentary Thermal Properties from Well Logs

The second phage of the project was estimation of the sedimentary thermal conductivity at each well site where the thermal gradient was obtained. Previous researches (Demongodin et al., 1991) suggested that it is possible to estimate the thermal conductivity by first constraining the mineral make-up of the formation and the porosity using a suite of wells, and then use the so-called mixing law in the heat conduction theories. (Demongodin et al., 1991) suggested use of the gamma-ray (GR), sonic (DT), bulk density (RHOB), and neutron porosity (NPHI) logs.

The work of actually estimating the thermal conductivities for the deepwater wells in this manner took a lot longer time than we originally anticipated. In order to perform the thermal conductivity estimation, we needed digital records of the logs for the entire depth of each well. We did acquire LAS-formatted logs for many of the wells being studies from the MMS archive. However, it turned out that only a small portion of the available records had been digitized in the LAS logs. Mike Jones and another graduate student in my lab (Sanketh Sangam) started digitizing other logs available only as scanned images, using the *NeuraLog* software, but their work made very progress.

There was another reason for the delay. The thermal conductivity estimation method suggested by (Demongodin et al., 1991) did not produce reasonable outcomes for our data sets. The reason of the failure, which we learned after carefully testing our methodology, was that this method would work only if the theoretical model prediction can be calibrated by actual thermal conductivity data measured on core samples from the formation where logs were obtained. Since no core samples were made available, this methodology did not work.

We needed to devise a totally new methodology to estimate the thermal conductivity from well logs. With help from Dr. George Asquith at our department, we developed a method that utilizes the volume ratio between shale and sand and the porosity of the formation. Such information was obtained from interpreting gamma-ray and porosity logs. We compared the conductivity predictions based on this new methods with typical thermal conductivity values found in previous measurements made on core samples from the sediments along the Gulf coast (McKenna et al., 1996). Using this method, we produced thermal conductivity-versus-depth curves for 55 wells.

We also estimated radiogenic heat production rate of sediment for some wells where natural gamma-ray spectrometer (NGS) logs were available. NGS logs yield the concentrations of Uranium, Potassium, and Thorium, which are the three dominant heat producers. Where NGS logs were not available, we used empirical relationship between the heat production rate and the conventional gamma-ray logs.

Heat flow in the Deepwater Gulf

Using the well VRTs, bottom-water temperatures, and thermal conductivity estimates, we determine the geothermal heat flow at 55 well sites. The heat flow was obtained as the slope of the so-called Bullard plot of the temperature versus thermal resistance (the depth-cumulative sum of the reciprocal of thermal conductivity). The heat flow values did show considerable variation among the well sites. Detail interpretation is provided in the attached Mike Jones' thesis. We learned that two factors strongly influence the geothermal field: (1) Proximity to salt structures and (2) Pleistocene sedimentation rates.

We were not able to construct realistic thermal history (and maturation) models for these well sites. There were two primary reasons. First, we simply ran out of time because of the delay we experienced in the thermal conductivity phase of the project. We proposed to carry out the work in 18 months in conjunction with the master's thesis work of Mike Jones. He had done enough work to graduate, but we could not complete all of the work we originally hope to accomplish. The second reason was that there was not enough information available to reconstruct the sedimentary burial history at each well site. We originally hoped to rely on the biostratigraphic database obtained from MMS (2001) for such information, but the database turned out to be lacking data from the deepwater part of the Gulf. Also, there were not detailed enough seismic stratigraphic studies previously published. The seismic interpretation of our study areas is very complicated due to the salt diapirism. There was not detailed enough information for us to be able to date major stratigraphic boundaries identified in well logs.

Even though we could not construct thermal history and maturation models on the well sites, Kelly Opre Jones, graduate student who has been examining the heat flow data provided by TDI-Brooks International, were able to construct such models for areas of the eastern deepwater Gulf, farther offshore from our study area. Her was presented at the last meeting of the American Association of Petroleum Geologists Gulf Coast section in Baton Rouge, LA. A copy of her paper presented is attached to this report.

References

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McKenna, T. E., J. Sharp, Jr., and F. L. Lynch, 1996, Thermal conductivity of Wilcox and Frio sandstones in south Texas (Gulf of Mexico basin): Amer. Assoc. Petrol. Geol. Bull., v. 80, p. 1203-1215.

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Nagihara, S., J. G. Sclater, L. M. Beckley, E. W. Behrens, and L. A. Lawver, 1992, High heat flow anomalies over salt structures on the Texas continental slope, Gulf of Mexico: Geophys. Res. Let., v. 19, p. 1687-1690.

LIST OF ATTACHMENTS:

M.S. Thesis of Michael Jones "The Regional Geothermal Heat Flow Regime of the North-central Gulf of Mexico Continental Slope".

A preprint of the paper presented by Michael Jones at the annual meeting of the Gulf Coast Association of Geological Societies in October 2003 in Baton Rouge, LA.

A preprint of the paper presented by Kelly Opre Jones at the annual meeting of the Gulf Coast Association of Geological Societies in October 2003 in Baton Rouge, LA.

CD-ROM containing digital files of heat flow estimates at individual wells and *ArcGIS* maps showing the locations of the wells.

TECHNICAL PRESENTATIONS OF THE RELATED WORK

The American Association of Petroleum Geologists Student Expo was held on October 20 – 21, 2002 in Houston, TX. Mike Jones and Kelly Opre Jones gave poster presentations there on their work described above.

Mike and Kelly each also presented a paper on their work at the annual meeting of the American Association of the Petroleum Geologists Gulf Coast Section. The meeting was held on October 22-24 in Baton Rouge, LA. Their papers are in the Conference Proceedings volume. Copies of each are attached to this report.

The annual national meeting of the American Association of the Petroleum Geologists will be held in April 2004 in Dallas, TX. I am planning to give a poster presentation the final outcome of this project together with my additional work in the eastern Gulf of Mexico.